## TITLE OF THE INVENTION

# Apparatus for Sealing and Restraining the Flexible Pressure Boundary of an Inflatable Spacecraft

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

The present invention relates to the field of seal and restraint systems for the establishment of a pressure boundary on inflatable or expandable structures in a vacuum environment. In particular, the present invention relates to the establishment of a pressure boundary between the flexible and the rigid materials of construction utilized on inflatable spacecraft such as orbiting satellites, space stations, and space vehicles, or any other type of space habitat.

### 2. Discussion of the Prior Art

Inflatable structures for use in space applications utilize flexible, non-rigid materials of construction to develop and maintain an inflatable pressure boundary over a substantial portion of their structure. Augmenting these non-rigid materials of construction are rigid materials that are necessary to form such components as hatches and docking mechanisms. A long-standing problem has been the development of a means to connect the non-rigid, flexible materials of construction

to the spacecraft's rigid structural components to establish a substantially air tight pressure boundary. Compounding this problem is the lack of any single material that has both the requisite gas impermeability, and the strength needed to withstand internal pressurization forces.

Because of a lack of a single suitable material, both a gas membrane and a restraint layer are required to establish an effective pressure boundary. The gas membrane is interior to the restraint layer and is typically a polymeric sheet material. This polymer is substantially impermeable to atmospheric gases to minimize air leakage into space. The restraint layer carries and distributes the internal pressurization loads imposed by the gas membrane.

The prior art has been unable to develop a fully satisfactory method to effectively establish a pressure seal between a flexible pressure barrier and a rigid component. It is the connection of the gas membrane and the restraint layer to the spacecraft's rigid structural components that has proven to be problematic. The best that the prior art has been able to accomplish is the development of a vise like connection mechanism that clamps both the gas membrane and the restraint layer to the rigid structural components of the spacecraft.

This prior art connection has several shortcomings that prevent the full and economic utilization of inflatable spacecraft. One of the most significant deficiencies is that the clamp mechanism must exert tremendous compressive force on the restraint layer and the gas membrane. This compressive force is necessary to resist

the pull out forces caused by the spacecraft's internal pressurization. These pull out forces in turn create shear stresses in both the restraint layer and the gas membrane.

The gas barrier, because of the special polymeric sheet materials needed to prevent air leakage, is generally thin, delicate, and prone to a variety of stress failure mechanisms. The clamp compressive forces and the induced shear stresses are sufficient to distort and damage not only the gas membrane, but also the restraint layer. Although the restraint layer is made from very strong materials, the threads from which these fabrics are woven can still be damaged by the clamp mechanism. Because of these compressive and shear forces, the load rating of the restraint layer is degraded. Consequently, the prior art vise like clamping mechanism is a poor method for connecting the gas membrane and restraint layer to the spacecraft's rigid structural components.

In addition to the clamping stresses that are directly imposed on the gas membrane, the restraint layer itself induces stresses in the gas membrane. As noted above, the prior art clamps the restraint layer and gas membrane together in a vise like grip. This causes the restraint layer and the gas membrane to act like a single component. This results in the transfer of forces from the restraint layer to the gas membrane. The interface of the highly stressed restraint layer with the gas membrane can cause a failure several ways.

The first failure mode results from the transfer of tensile forces in the restraint layer to the gas membrane, causing the gas membrane to be placed in tension. This tensile

stress further induces shear stresses in the gas membrane because of the restraint imposed by the clamp. The gas membrane can then fail in either tension or shear.

The gas membrane may also fail as a result of fatigue. Constantly fluctuating spacecraft air pressure can cause alternating stresses in the restraint layer that are transferred to the gas membrane. The constant movement of the restraint layer against the gas membrane may cause fatigue failure of the gas membrane. The gas membrane may also fail due to abrasion caused by the relative movement of the restraint layer against the gas membrane.

Another problem with the prior art design relates to the effectiveness of the air seal created by the clamping mechanism and the gas membrane. Because both the gas membrane and the restraint layer are clamped together, (back to back against an o-ring) sufficient compressive forces may not be available to ensure a leak tight seal. This is a result of the relatively thick, deformable nature of the restraint layer and its susceptibility to creep under a compressive load. Because of deformation and creep, the restraint layer continues to flow away from the location of the imposed compressive force. Consequently, the compressive force against the o-ring is gradually reduced, and the hermetic seal is degraded or lost.

Internal air pressurization further contributes to seal degradation. Internal air pressure works between the gas membrane and the o-ring, urging the gas membrane off the o-ring and reducing the effectiveness of the seal. Compounding this problem is the potential for the development of wrinkles in the restraint layer fabric. These wrinkles may propagate over the gas membrane and the o-ring seal.

Air pressure may then force the gas membrane off the o-ring and into the wrinkled area of the restraint layer, thus forming an air leakage pathway.

A similar prior clamping connection is shown for an inflatable lunar habitat as discussed in "Deployable Lunar Habitat Design and Materials Study, Phase I Study Program Results", developed for the NASA Johnson Space Center. The inflatable habitat discussed in the NASA report differs from the present invention in at least one other profound respect. The habitation has a fixed, unexpandable diameter that only allows axial expansion.

The inability of the prior art design to expand diametrically severely restricts the principal advantage of inflatable spacecraft technology. That is, the ability to minimize the volume of the launch package, and maximize the deployed inflated volume. In fact, the diameter of the launch vehicle is generally the limiting dimension for almost all launch payloads. The inability to utilize the prior art to obtain an expansible diameter is an additional handicap that undermines the development of inflatable spacecraft. Consequently, a new connection mechanism is needed to provide an inflatable spacecraft with an expansible diameter.

In summary, the prior art designs are inadequate to provide a reliable and effective pressure boundary. As noted above, the prior art seal and restraint system subjects the restraint layer and the gas membrane to excessive stresses that can damage either or both of these components and result in structural failure. The prior art also allows excessive air leakage losses between the gas membrane and the o-ring. Furthermore, the prior art does not allow the gas membrane layer to be replaced

without disassembling the restraint layer. For all of these reasons, the prior art design is inadequate, and a new sealing and restraint system is needed to make inflatable space structures economical and reliable.

## SUMMARY OF THE INVENTION

The present invention provides a novel apparatus for establishing an effective seal and restraint system that can anchor a flexible pressure boundary to the rigid structure of an inflatable spacecraft. The importance of the present invention is that it can establish a substantially hermetic seal between a flexible pressure boundary and a rigid structure with sufficient strength to allow the spacecraft to operate in a vacuum while internally pressurized.

The present invention establishes a pressure boundary using both a restraint layer and a gas membrane that cooperatively act to seal and restrain the pressure boundary to the spacecraft's rigid structural components. No significant tensile stresses are imposed on the gas membrane because it is oversized and located inside the restraint layer volume in which it is constrained.

The present invention uses separate attachment connections for the gas membrane and the restraint layer. The separation of these two attachment mechanisms isolates the sealing system from the restraint system, while at the same time allows the gas membrane to interact with the restraint layer over the remainder of the gas membrane surface area.

The gas membrane attachment mechanism establishes a substantially air tight seal, while imposing negligible stresses on the gas membrane. This has been accomplished using a free floating compression seal, which traps the gas membrane between at least

one elastomeric seal (e.g., o-ring seals) and a flange, or preferably, between a pair of elastomeric seals. The only forces exerted on the gas membrane are the compression stresses at the seal contact point. This seal isolates the gas membrane from tensile stresses while providing a very effective pressure seal. This allows the gas membrane to float between the seals, thereby preventing any significant stresses from developing on the gas membrane.

The restraint layer attachment mechanism prevents crushing of the restraint layer and minimizes stress concentration factors while evenly distributing the restraint layer loads to the spacecraft's rigid structural components. Loops at the ends of the restraint layer transfer internal pressurization loads to a retaining member in the rigid spacecraft structure. The restraint layer loops are free to pivot about the retaining member to minimize stresses on the loops and the restraint layer. If desired, an anti-chafing protective sleeve can be placed over the loop to prevent abrasion damage to the restraint layer loops. The retaining member itself is trapped between two flanges that allow the retaining member to evenly transmit the restraint layer forces into the mating flanges.

From the brief summary provided above it can be seen that the present invention provides many advantages over the prior art and has the following specific objects:

One of the objects of the present invention is to provide a substantially leak tight seal between the gas membrane and its connection point to the spacecraft's rigid structural components without unduly stressing the gas membrane. This has been accomplished using a free floating compression seal.

Another object of the present invention is to provide a more effective air seal by eliminating the restraint layer to gas membrane interface found in the prior art. The present invention eliminates this interface, establishing two separate anchoring mechanisms for the gas membrane and the restraint layer.

Another object of this invention is to minimize mechanical damage to the restraint layer at the connection point to the rigid structure. This has been accomplished in the present invention using a plurality of restraint loops placed around a retaining member held in place by a flange assembly.

In summary, the present invention minimizes air leakage, maximizes gas membrane service life, minimizes stresses imposed on the gas membrane and restraint layer, provides a diametrically expansible structure, and allows the gas membrane to be replaced without removing the restraint layer. These are all significant technical advancements over the prior art. The technological advancements of the present invention substantially increase the commercial viability of inflatable spacecraft.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross sectional view of the pressure barrier seal and restraint apparatus.

FIG. 2 is an isometric view of the pressure barrier seal and restraint apparatus.

FIG. 3 is an exploded isometric view of the pressure barrier seal and restraint apparatus.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Preferred embodiments of the present invention that illustrate the best modes now contemplated for placing the invention in practice are described as follows, and in conjunction with the attached drawings that form a part of this specification. The preferred embodiments are described in detail without attempting to show all of the various forms and modifications in which the present invention may be embodied. The preferred embodiments described are illustrative, and as will become apparent to those skilled in the arts, can be modified in numerous ways within the spirit and scope of the invention, the invention being measured by the appended claims and not by the details of the specification.

The present invention is a restraint and sealing system for use in inflatable space structures that utilizes a flexible, non-rigid pressure boundary. Examples of the construction techniques utilized in the development of these inflatable space structures is provided in Deployable Lunar Habitat Design and Materials Study, Phase I Study Program Results", developed for the NASA Johnson Space Center, under Purchase Order #T-357-5V, hereby incorporated by reference. FIG. 1, FIG. 2, and FIG. 3 depict the present invention with the seal and restraint system, as it would be installed in a typical inflatable spacecraft. The present invention utilizes a gas membrane **60** and a restraint layer **50**. The gas membrane provides an air seal against the vacuum of space. The restraint layer contains the internal pressurization forces created by the pressure differential between the vacuum of space and the space structure's internal pressure.

The gas membrane and the restraint layer work, function, and interact cooperatively to form the pressure boundary of the spacecraft.

The gas membrane **60** is typically composed of polymeric sheet material, and is inside the restraint layer volume. The gas membrane is independently attached to the rigid spacecraft structure between a seal flange **10** and the base flange **20** to establish a substantially hermetic seal. The gas membrane is oversized so that its fits loosely inside the restraint layer **50**. This allows the gas membrane to expand against the restraint layer **50**, transferring the internal pressurization forces to the restraint layer. This configuration minimizes tensile and shear loads on the gas membrane. Although this places the gas membrane in compression, as with most materials, polymeric materials are able to withstand compressive forces quite readily. This load configuration is critical, because the gas membrane is generally thin and delicate. Consequently, the gas membrane must be fully supported over its entire surface area to prevent its extrusion through the restraint layer.

To ensure that the gas membrane **60** is not extruded through the restraint layer **50**, some restraint layer designs may require a carrier layer **52**. The carrier layer is preferably attached to the restraint layer, although it may be attached to the gas membrane, or simply placed between the gas membrane and the restraint layer. The carrier layer **52** covers any voids or discontinuities that may be present in the restraint layer. The carrier layer **52** prevents the extrusion of the gas membrane and provides the added benefit of providing a smoother surface for the gas membrane to push against, minimizing stresses and abrasion on the gas membrane.

In the preferred embodiment, the gas membrane **60**, to be fully protected from the hard surfaces at the attachment point, is sandwiched between elastomeric seals, such as o-rings **61, 62**. These o-rings may ride in a groove provided on the mating face of the seal flange and the second face of the base flange. These o-rings substantially isolate the gas membrane from potentially damaging attachment point stresses. The only stresses imposed by the o-rings are compressive stresses on the trapped portion of the gas membrane. It is this compression seal that provides a substantially airtight seal between the rigid spacecraft structure and the gas membrane. If desired, to simplify the design of the sealing system, a single seal may be used to trap the gas membrane between the seal and either the mating face of the seal flange **10** or the second face of the base flange **20**. This configuration although simpler, has the potential for significantly more wear on the gas membrane.

Normally, the internal pressurization forces the gas membrane to conform against the restraint layer, preventing the gas membrane from slipping out from between the seals. A deadman may be used, if desired, to ensure that the gas membrane is not accidentally pulled from between the o-ring seals. This feature provides positive backup to prevent the possible retraction of the gas membrane from between the seals.

The deadman **63** may be formed by doubling the gas membrane **60** to form a substantially thicker portion at the edges of the gas membrane. This increased thickness may be heat sealed, sewn, or otherwise maintained in place. Alternately, a rigid member may be attached to the gas membrane **60** to form the deadman. The deadman may be placed in the cavity **11** formed between the mating face of the seal

flange **10** or the second face of the base flange **20**. Although the deadman **63** fits into cavity **11**, it cannot be extruded because the deadman is larger than the clearance between the base flange **20** and the seal flange **10**.

The restraint layer **50** is typically made from polymeric materials such as Kevlar or Vectran. These materials are typically woven to provide a high strength, yet flexible material. The restraint layer may take many different forms and shapes. For example, the restraint layer may be made from sheet materials, straps, or formed using a basket weave type construction. The restraint layer may take on any form, use any type of construction, or be made from any material, provided that the restraint layer has the ability to be expand from a collapsed position into a fully deployed position when inflated.

The restraint layer **50** is connected to the rigid spacecraft structure to form an enclosure within which the gas membrane is contained. The restraint layer, in a substantially cylindrical structure, experiences stresses that are essentially equivalent to the standard hoop, axial, and shear stresses associated with any cylindrical pressure vessel. The restraint layer must be connected to a rigid structure in a way that allows the stresses to be evenly and uniformly distributed, throughout the restraint layer as well as the rigid structure.

To uniformly distribute the internal pressurization forces, the present invention utilizes a retaining member **40**. The retaining member is held in place with a base flange **20** and a locking flange **30**. The first face of the base flange **20**, in conjunction with the mating face of the locking flange **30**, contact to create a series of recesses **23**. The recesses **23**

extend from under the retaining member, and exit through the outer surface around the circumference of the base flange **20** and the locking flange **30** at their interface. Located between each of these recesses is a passage **24** that connects to, and is in communication with each adjacent recess. These passages are for capturing the retaining member **40**.

Connected to the restraint layer **50** is a plurality of loops **51** that are attached at one end to the restraint layer, and at the other end attached to the retainer member. The restraint layers loops **51** fit inside the recesses and extend around the retaining member **40**. The restraint layer loops uniformly distribute the stresses in the restraint layer to the retaining member. The retainer member, by virtue of its continuity around the mating flanges distributes the restraint layer loads uniformly around and into the rigid structure. The retaining member and enclosing flanges minimize abrasion, fatigue, and stresses on the restraint layer **50** or the restraint layer loops **51**.

Even with the carrier layer, additional protection for the gas membrane may be desirable at the point where the restraint layer loops enter their respective recesses. To ensure that the gas membrane is not pinched between the loops and the flanges, or otherwise extruded between the loops, a dam **65** may be placed around the outer circumference of the base flange, between the restraint layer and the gas membrane. The dam **65** may be captured in a groove around the base flange. Alternately, bolt hole recesses around the circumference of the base flange may be used to hold the dam. This provides the further benefit of protecting the gas membrane from the discontinuities presented by the bolt heads.

The dam diverts the gas membrane away from the recesses and prevents the extrusion of the gas membrane. The dam is preferably made from a compressible elastomeric material, allowing the force of the gas membrane to compress the dam against the restraint layer. The conformance of the dam to the restraint layer ensures the elimination of any spacing between the dam and the restraint layer, preventing the pinching or extrusion of the gas membrane.

The retaining member **40** itself may be formed from separable components to allow the loops in the restraint layer to be preformed, ready for assembly. During assembly, the restraint layer loops are placed around the retaining member, and the retaining member may be assembled into a single component. The retaining member **40** is in turn placed between the base flange **20** and the locking flange **30**. The locking flange and the base flange are connected together to trap the retaining member. Similarly, the seal flange and the base flange are connected together to form the compression seal holding the gas membrane. The entire assembly may then form an opening for a spacecraft hatch, bulkhead, or docking mechanism.

Although it is not necessary, the flange assembly (base flange, the locking flange, and the seal flange) may be further attached around a rigid member **100** to build upon the spacecraft's structure. The rigid member **100** may be hollow to provide access for a hatch, docking mechanism, or view port. Alternately, the ends of the base flange **20** may be extended to take the form of rigid member **100**. However, neither the rigid member, nor extension of the base flange is necessary, and only represent different embodiments of the present invention with greater structural rigidity.

In summary, the present invention described herein provides a very low leakage seal and restraint system that can be used to establish and maintain the pressure boundary around an inflatable spacecraft. Although the present invention has been described above with reference to certain preferred embodiments, it is understood that modifications and variations are possible within the scope of the appended claims that follow. Among these variations is the potential to use the present invention to affix the pressure boundary using a single retainer member to form a single opening in the flexible pressure boundary. Alternately, multiple retainer members may be used to form any number of openings for hatches, docking mechanisms, or viewing ports.